DEVELOPMENT OF TEMPERATURE AND HUMIDITY-BASED INDICATORS FOR DIAGNOSING PROBLEMS IN LOW TONNAGE, SPLIT SYSTEM AIR CONDITIONERS

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ABSTRACT

This paper presents results of a survey of the literature and identifies the most common degraded conditions associated with low-tonnage air conditioners. Other laboratory studies as well as marketed diagnostic systems are also summarized. A procedure for identification of useful, low-cost temperature-based indicators of degraded conditions has been developed at the Energy Systems Laboratory, Texas A&M University in College Station, TX under contract to Honeywell. This paper presents the methodology used to identify the temperature-based indicators for the most common degraded conditions gleaned from the literature.

BACKGROUND

It is common for automated monitoring and control systems to be applied to large scale HVAC systems found in large buildings. Many times these take the form of well-known building automation systems (BAS) and energy management and control systems (EMCS) with powerful microprocessor-based distributed control modules networked with central monitoring equipment such as PC's with large amounts of read-write memory available for data storage and manipulation. These systems have been shown to be useful for troubleshooting and the application of failure detection and diagnosis (FDD) techniques which help the operator to keep equipment operating at designed performance levels as well as maintain savings or keep operating costs at a minimum as a result of the improved maintenance. However, few applications to small-scale HVAC systems such as those found in residential and light commercial applications have been implemented due to the high cost of microprocessor-based equipment and on-board memory in past years. Recent improvements and technological advances have driven the cost of such resources down to a level that could justify application to the smaller units.

This paper is a summary of a portion of the original work (Watt 1997) in which a split-system direct-expansion air conditioner was used to empirically determine temperature-based indicators that, together with one return-air humidity point, could detect performance deterioration resulting from equipment or system degradation. The air-conditioner test bench was equipped with the ability to use either a short-tube orifice (STO) or a thermal expansion valve (TXV). The degraded conditions studied include low evaporator airflow, high- and low-charge, and a blocked condenser coil.

The empirical work was performed to identify degraded effects that fall outside of a simulation-based approach. It sought to utilize only low-cost temperature sensing means, although return-air humidity was also identified as an important factor for obtaining early detection over a wide range of operating conditions. Further, the original work sought to differentiate between a system that uses a short-tube orifice (STO), or fixed-orifice expansion, and a system that uses a thermal expansion valve (TXV), or variable-orifice expansion.

The original work showed that low-cost temperature sensors can be used to detect the degraded conditions studied. However, it also showed that the temperature-based indicators of low evaporator airflow depend on three loading factors; outdoor-air temperature, return-air temperature, and return-air humidity. The original work did not include an investigation of the effect of the three loading factors on temperature-based indicators for improper charge or blocked condenser coil. In the literature, the return-air humidity sensing point has been neglected by previously published automated detection systems for failures and degraded conditions of low-tonnage air conditioners.

Finally, while there were differences in the performance of a STO system and a TXV system relative to the degradations studied, a common set of indicators was identified that could detect the degraded conditions studied without regard to the expansion device.

LITERATURE REVIEW

Field Studies of Component Failures and Degradations

Several sources have provided field data involving the frequency of component and system failures and degradations. Neal (1987) surveyed ten residential split direct-expansion (DX) air-conditioning units. In this study, Neal suggests leading causes for inefficiencies to be improper charge and improper system airflow both of which can originate at installation. Neal states that errors in installation alone can result in efficiency losses of 25% or more. An 18 month survey by Air Conditioning Training and Consulting in cooperation with Murphy Engineering of Phoenix, Arizona (ACHRN 1988) resulted in similar findings and pointed to dirty evaporator coils, dirty condenser coils, and improper charge as the leading causes of system inefficiency. A telephone survey of 492 HVAC dealers and contractors by Lewis (1987) lists refrigerant leaks and fan failures as the most common causes of service calls. Karger and Carpenter (1978) studied component failures and determined that electrical component failures were most common followed by refrigerant leaks, compressor failure and outdoor fan failure. A summary of maintenance procedures of air conditioner on a university campus in Dhahran was compiled by Zubair (1989), which divides procedures into general categories led in frequency by electromechanical related, controls related, and filter problems.

In 1984 the Louisiana Cooperative Extension Service reported on a series of demonstrations intended to place a monetary value, in terms of energy bill savings, on preventive maintenance programs for residential air-conditioners (Smilie et al. 1984a,b). The air conditioning system in each of five residences was evaluated before and after a thorough system tune-up including chemically cleaning condenser and evaporator coils, filter replacement, blower wheel cleaning, factory specified charging and fixing duct leaks. Results based on 8 cents/kWh and outdoor air conditions ranging from 88 to 92 °F showed that, on average, the tune-up restored ½ to 1 Ton in cooling capacity and saved the home owner $32.76 in one month. Leading causes of degradation in performance cited in this study were dirty condenser coils, dirty blower wheels, improper charge, and return-air plenum leaks. In a related study in which a similar tune-up was performed on six small-business air-conditioners it was confirmed that significant loss of cooling capacity and efficiency resulting in higher utility bills, $29.70 for one month on average, is a direct result of the lack of proper maintenance or installation.

Results from a study by Proctor Engineering Group (Proctor 1991) show that potential energy consumption savings resulting from system repairs or tune-ups include 8% for correcting low airflow, 12% for correcting overcharge, 12% for correcting undercharge, and 18% for correcting duct leakage.

Based on results presented in these field studies it is concluded that, outside of electrical problems, improper airflow on both the evaporator and condenser side as well as improper charge are the most common degraded conditions encountered in the field resulting in significant and measurable loss of efficiency. Further, these studies show that occupancy comfort and equipment longevity both suffer as a result of these problems whether due to improper installation or slow degradation over time.

Laboratory Studies of Degraded Conditions

Further measurement of the ill effects of degradations that have been shown to be common in the past have also been documented in laboratory tests. Houcek and Thedford (1984) investigated the potential for compressor failure due to improper charge and showed that low charge can cause insulation breakdown and high charge can cause liquid slugging, both shorten compressor life. Another study by O'Neal and Farzad (1990) concluded that system efficiency decreased as a result of high- and low-charge. Neal and O'Neal (1992) confirmed findings in the previous works and showed that a peak or optimal performance point exists corresponding with the proper charge at a given set of conditions. Later, Farzad and O'Neal (1993) investigated the effect of improper charge using different kinds of expansion and showed that a fixed form of expansion such as a capillary tube is more sensitive to improper charge than a variable type of expansion such as a thermal-expansion valve (TXV).

Rodriquez (1995) ran a series of tests which confirmed earlier works findings about improper charge as well as the effects on performance due to improper system airflow and duct leakage. Results from these tests further confirmed differences in the response of a system using a short tube orifice (STO), a fixed form of expansion, and that of a system using a TXV. Namely, the TXV was able to respond to a given degraded condition by restricting or allowing more refrigerant flow thus compensating somewhat for the degraded condition. Further, Rodriquez's results suggested that a correlation exists between a given degradation and measurable system characteristics such as superheat and subcool. Other studies confirmed this finding in the form of temperature-based indicators including Palani (1992) and Payne and O'Neal (1994). Palani, who showed that low evaporator airflow can result in significant loss of efficiency and capacity, suggested some temperature-based indicators that could provide an early warning of low evaporator airflow and thus avoid the added cost of operating the system, if the problem is corrected. Similarly, Payne and O'Neal (1994) identified a temperature-based indicator useful for identifying and measuring a degradation in the outdoor airflow during frost build-up conditions. They also showed that the data did not correlate as well with a TXV as was found for the system using a STO.

The literature has shown that degradations over time and system installation errors can and do cause significantly reduced system longevity as well as increased energy requirements, system operating costs and ultimately occupant discomfort. Further, the literature has shown that indicators exist that do correlate with some of the most common degraded conditions found in the literature. It is the belief, based on the literature, that the more subtle but costly consequence of higher energy bills and electrical demand can be avoided during early stages prior to the obvious discomfort caused in later stages that led to the original work.

In the original work Watt (1997) gives many examples of common indicators and tools used by field technicians to help speed the diagnosis of system problems including those offered by Snyder (1993), Wheeler (1991), ACHRN (1991), Wren (1994), Lloyd (1994) just to name a few. Many of these tools, rules-of-thumb, and indicators are useful for field diagnosis while some are not so great such as the "touch" method of determining if a system is charged properly. Further, some of the methodologies require something that many technicians are simply not willing to invest... time. This is in part due to the fact that service calls tend to occur in large groups during heat-waves and at the beginning of the cooling season when many problems manifest themselves in the form of insufficient cooling or failed equipment. The literature also suggests that improper installation, shown in the literature to be a significant source of inefficiency, may be due to a lack of properly trained technicians (Neal 1987; Silver 1989; Lewis 1987; Karger 1978; Skaer 1994, 1995) who do not realize the importance of or simply ignore correct procedure when installing a new system. The original work lays the ground-work for a system that could relieve some of the burden of troubleshooting by providing early warning for owners and service companies by not only identifying the specific problem but could inherently spread the frequency of service calls during peak times.

Automated Detection of Failures and Degraded Conditions

A number of systems have been developed over the past decade which sought to realize, in some form, the type of system just described. Ogden (1993) describes a system used by a service technician from Portland, Oregon which utilizes a number of temperature and pressure sensors strategically located throughout an air-conditioning unit. The sensors are permanently installed and wired back to an easy-access box for quick reading using a hand-held reader. Ogden claims that with the help of a computer program, the data can be entered into a database of previously recorded readings from a particular unit and used to detect subtle changes in the performance of the system. The original work reveals that evaporator return-air humidity is an important parameter when correlating temperature data to changes in performance. Ogden did not mention a humidity sensor as one of the measurement points. Further, intermittent problems were admittedly difficult to detect using the described system.

While the system described by Ogden was not automated (readings were taken and entered into the computer program by hand) a couple of systems have been marketed which utilized integrated data acquisition and data-logging together with the power of recently widely available microprocessor-based technology to automatically gather, store, and analyze data in real-time. These systems were also capable of initiating an alarm when a problem was detected and describing the type of problem in the form of a code. These systems were designed specifically for small air-conditioning units and applications and should not be confused with their amply sophisticated cousins known as building automation systems (BAS) or energy management control systems (EMCS). For more information on automated failure detection and diagnostics (FDD) of large, complex building HVAC systems, the reader is referred to ASHRAE (1996), Dexter and Benouarets (1996), Usoro et al. (1985), Haberl et al. (1988), Haberl et al. (1989), Pape et al. (1991), Hyvarinen (1993), Lee et al. (1996), Ahmed et al. (1996).

Kaler (1988, 1990) developed an expert system (or rule-based system) for detecting changes in performance of a residential air-conditioner in real-time. The system was manufactured and marketed by Kaler's Dallas-based company, Woolery Technology. The rule-base used by Kaler was developed through interviews with "experts" and claimed the ability to "learn" the normal operating profile of a given air conditioner. Kaler claims the system could detect deviations from the normal operating profile and, based on the expert rule base, determine the source of the problem.

Another system developed by York called the YorkGuard IV uses temperature, pressure and voltage inputs to detect "dangerous" operating conditions and, in the event of a positive detection, will lock out operation until the unit is serviced (ACHRN, 1995).

Dencore markets a system called the Cool Guard ACM-88 (Dencore, 1994) which claims the ability to identify refrigerant leaks, dirty filters, fan failures, low efficiency, and high water in the condensate pan using only five sensors: outdoor-air temperature, return-air temperature, middle temperature (between the cooling coil and heating coil), supply-air temperature, and a condensate pan float switch.

The systems described by Kaler (1988), York (ACHRN, 1995), and Dencore (1994) are superior to the system described by Ogden (1993) in the sense that real-time data is utilized and therefore may detect problems more promptly and thus save equipment and money. However, it is unknown whether or not they are superior in diagnostic ability.

Perhaps the most important recent development in the area of small-scale HVAC FDD found in the literature was work done at Purdue by Rossi (1995). Rossi studied the detection, diagnosis and evaluation of faults in vapor compression cycle equipment. He developed a model by which evaluation of degraded conditions such as fouled coils, leaky compressor valves and restricted liquid-lines could be achieved using a microprocessor-based system. His simulation-based approach showed that small changes in operation due to degraded conditions such as improper refrigerant charge could be evaluated by generating a statistical confidence level of the error in actual measurements versus the expected, or simulated, value. The real-time simulation, which uses only manufacturer's data for tuning, could be a valuable tool for evaluating faults if the cost of the high-speed computation equipment required for a real-time simulation can be justified.

The intent of the original work is to develop a cost-effective system that uses only low-cost temperature sensors and has very little computational needs. Therefore, an empirical approach to identifying indicators is used in the original work which seeks to improve on the automated systems found in the literature by taking into account three loading factors: return-air temperature, return-air humidity, and outdoor-air temperature.

To summarize the findings in the literature, the three most common root problems that result in costly equipment replacement and higher energy bills were improper system airflow, improper refrigerant charge, and electrical/control problems. While controls and miscellaneous electrical faults represent a significant portion of the top three root problems, they were not specifically addressed in the original work. Other degradations and failures were identified such as refrigerant line restrictions, faulty metering (expansion) devices and compressor problems such as leaky valves which were not addressed in the original work. The original work focused on the two problems which together take the largest share of root system problems, improper airflow (evaporator and condenser) and improper charge.

EXPERIMENTAL APPARATUS

The test bench used to create the degraded and failed conditions is shown in Figure 1. The test bench was constructed in two separate sections, each on a movable table, so that the entire bench could be moved into the split psychrometric chamber with minimal disassembly and setup time.

The evaporator section consisted of a bank of three standard flow nozzles for airflow rate measurement and a flow settler positioned to Air Movement and Control Association Standards (AMCA 1985) to ensure an even flow profile entering the evaporator coil. The ductwork on the leaving-air stream was well insulated to minimize the effect of ambient conditions inside the lab.

The air sampling (psychrometric) stations were installed to measure both drybulb and wetbulb temperature entering and leaving the evaporator coil. The fans used to draw the air from the duct and through the psychrometric stations were sufficiently sized to provide the minimum 100 fpm airflow velocity required for wetbulb temperature measurement (McQuiston and Parker, 1988).

The evaporator coil, oriented perpendicular to the airflow, measured 28 inches wide by 18 inches tall and had four rows of tubes with four parallel circuits. The blower was placed after the coil in a draw-through configuration. The condensing unit contained the condenser coil, compressor and accumulator. The 48,000 Btu/h unit was typical of the outdoor section of split-system DX air-conditioning units seen on homes and businesses. The unit had heat pump operation capability, however, the heat pump mode was not used in these tests. The entire assembly is shown in Figure 2.

The evaporator section was connected to the condensing unit with copper tubing. The liquid-line was split into two parallel sections so that either a TXV or STO could be used as the expansion device to allow differences in operation of the two systems to be measured and documented.

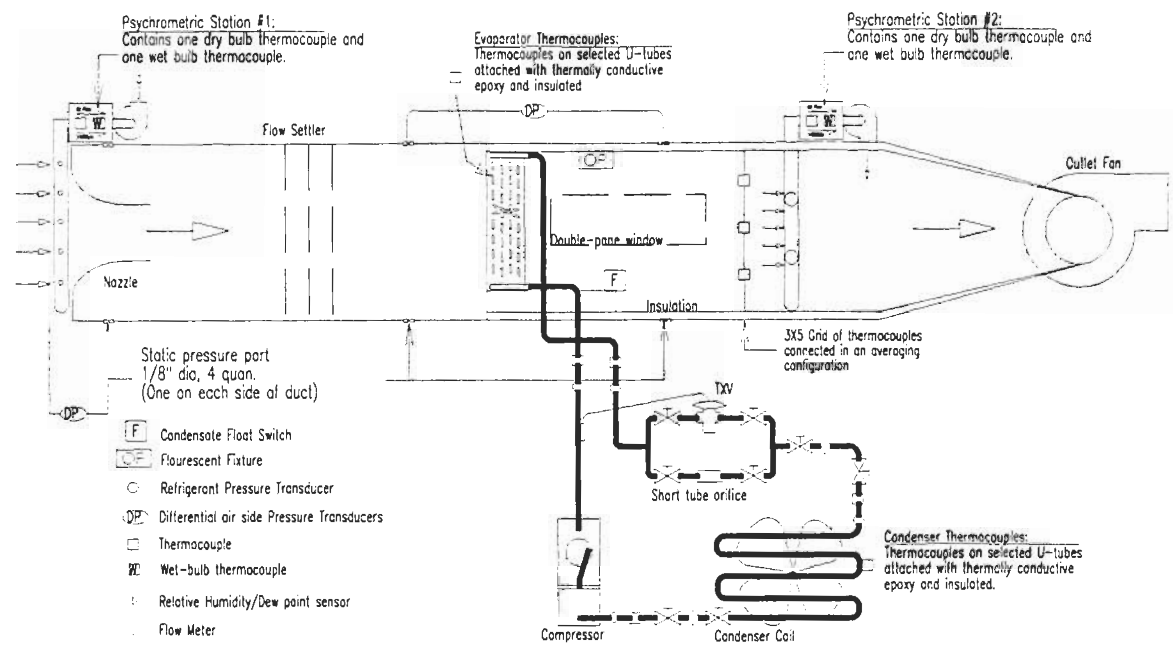

Figure 1. Experimental test bench used to characterize the degraded conditions in the original work

Thermocouples were T-type assembled with solid 24-gauge copper-constantan wire. Thermocouples mounted directly onto the copper refrigerant lines were used to measure the refrigerant-line temperatures. A hand-held Fluke thermocouple reader was used to check these readings by installing K-type thermocouples next to the T-type thermocouples connected to the DAS board in the manner described. The K-type thermocouples and the hand-held reader were also calibrated prior to installation. Additional details concerning the experimental set up can be found in Watt (1997).

Data were collected using a NetPac modular data acquisition system (DAS). A 33-MHz 80386 PC was used for monitoring and data collection. Following each test, the data were saved to floppy disk. Before beginning the next test, the data were visually inspected for "holes", or missing data. A complete list of all measured and calculated (virtual) points can be found in Watt (1997).

Some of the tests were performed in the controlled environment of split psychrometric chambers. The split psychrometric chambers at the Energy Systems Laboratory consisted of two large, well-insulated rooms. Each room could be temperature- and humidity-controlled using PID control. A photograph of the facility is shown in Figure 3.

During testing, the conditions in the room were monitored closely from within the control room to be sure that conditions did not deviate from the setpoints prescribed for each chamber. For these tests, the indoor room was controlled for temperature and humidity while the outdoor room was controlled for only drybulb temperature because no latent heat transfer to or from the air at the condenser coil.

METHODOLOGY

Experimental Procedure

The testing procedures, whether in the uncontrolled laboratory environment or the controlled psychrometric chambers, were similar. In each case, the system was evacuated, leak tested, and charged the desired amount using a digital scale to weigh the charge. Before charging, the system was purged with nitrogen and leak tested. When the system was found to have no leaks, it was charged with refrigerant.

Before beginning a set of tests, the sensors and data acquisition system were checked for proper operation. The first test of any set was a standard test at normal airflow rate, charge, etc. Following the standard test, the degraded tests were run individually varying in magnitude with increasing severity. In the uncontrolled environment, as a final step, the standard test was repeated to ensure that the ambient conditions within the lab had not drifted enough to significantly affect the results.

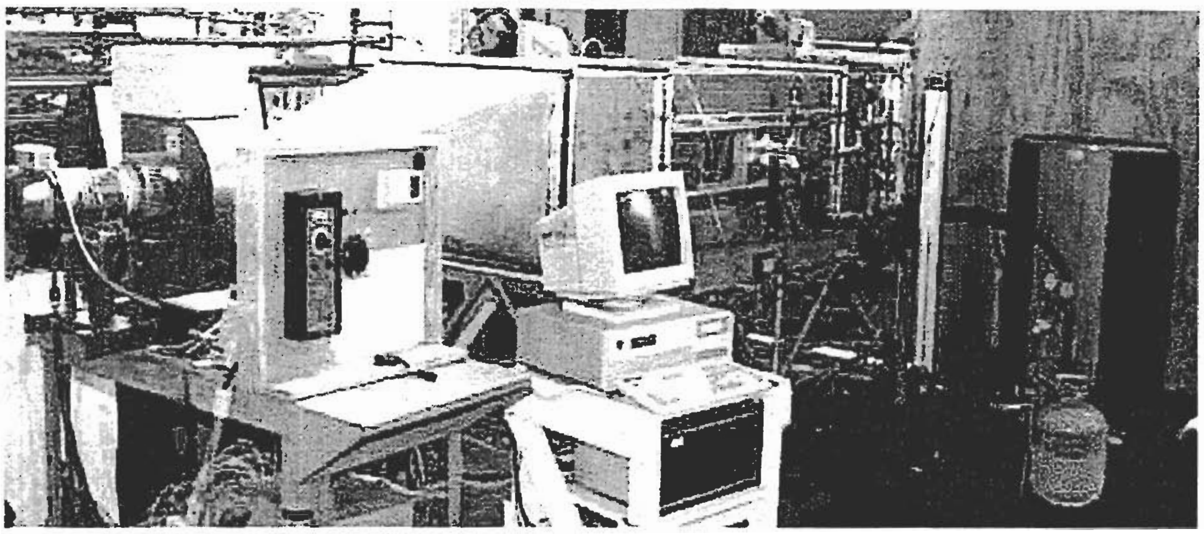

Figure 2. Photograph of the test bench shown in Figure 1

Each test lasted approximately 20 to 30 minutes, or enough time to obtain at least 15 minutes of steady-state data. The average of a measured or calculated point over the steady-state operating range was calculated and defined as the value for the point during a given test. A typical data set is shown in Figure 4 which illustrates the steady-state range over which the data were averaged to obtain the value of the data point.

Results from the STO System in an Uncontrolled Environment

The objective of the low-evaporator airflow tests was to empirically identify temperature-based indicators that can isolate this degradation, whatever the cause. In the original work, the airflow was varied by adjusting the speed of the indoor blower using a variable-speed drive (VSD). The airflow rate was calculated using the measured differential pressure across the flow nozzles. The differential pressure across the nozzles was monitored closely using a liquid micro-manometer which was more valuable as a visual reference than the digitized reading obtained from the DAS. A typical test set began with a standard 1400 CFM test and each subsequent test was reduced from the standard incrementally by 100 CFM. For those test sets performed in the uncontrolled environment, the final test was an additional standard 1400 CFM test to be sure that any changes in the uncontrolled testing environment did not significantly effect the test results. In this way, data were collected that could be used to identify temperature-based indicators that correlate with the decrease in evaporator airflow.

Figure 5 shows the drift in the ambient (return air) conditions as well as the effect of reducing the evaporator airflow on the leaving air conditions. Entering-air, or return-air, conditions (about 80°F and 55 – 60% RH) are indicated by circles and the leaving-air, or supply-air, conditions by squares. The return-air temperature drifted 2.8°F (3.3%) and the specific humidity drifted 0.0002lb_{water}/lb_{air} (1.4%) during the course of the ten tests in the uncontrolled environment.

The evaporator air temperature difference increases along with the enthalpy difference but the overall capacity, or heat removed from the air, decreases with decreasing airflow. The rate of heat transfer is related to the enthalpy of the air and mass flow rate by $q_{air}=m_{air}\Delta h_{air}$. Thus, the decrease in the mass flow of the air (m_{air}) had an effect on the rate of heat transfer (q_{air}) that was greater than could be overcome by the increase in enthalpy difference (Δh_{air}). If it is assumed that the refrigerant side of the circuit sees only the decrease in heat transfer then by extension, evaporator tube fouling could be characterized using the same refrigerant-temperature-based indicators as were identified in these tests. However, the air-temperature-based indicators, or those indicators using a combination of refrigerant- and air-temperatures, would not be applicable to evaporator fin fouling.

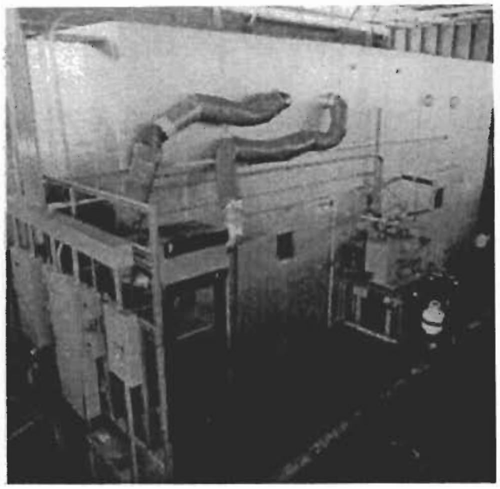

Figure 3. Psychrometric chambers at the EnergySystems Laboratory on the Texas A&M University Riverside Campus

Figure 6 shows the net effect of the decreasing airflow on normalized system performance parameters capacity, EER, and total power consumption. The values are normalized to their respective values at 100% airflow, 1400 cfm. The normalized system performance indicators are used to help identify temperature-based indicators by identifying the point at which the operation of the unit has degraded to a "critical point". Likewise, the effect of reduced evaporator airflow on superheat shown in Figure 8 also helps identify the "critical point" with respect to compressor safety.

Part of the problem in determining indicators for low airflow conditions is to determine the point where the airflow becomes "critical." Three parameters are used in the original work to define the "critical point" of low evaporator airflow. They are: cooling capacity, or the ability to meet the cooling load; the cooling efficiency (EER), or the cost of meeting a given cooling load; and equipment safety, or the ability to maintain equipment longevity by avoiding equipment-life-reducing conditions such as compressor slugging (no superheat) or lack of compressor cooling (high superheat) or seal stressing (high lift pressure).

Cooling capacity becomes critical when the comfort of the occupants or the quality of the environment in the space is compromised because the cooling equipment can no longer "keep up" with the cooling load in the space. For the purpose of this analysis, 15% was chosen as the "critical point" for a reduction in cooling capacity due to the common practice of many designers to add a "safety factor" of

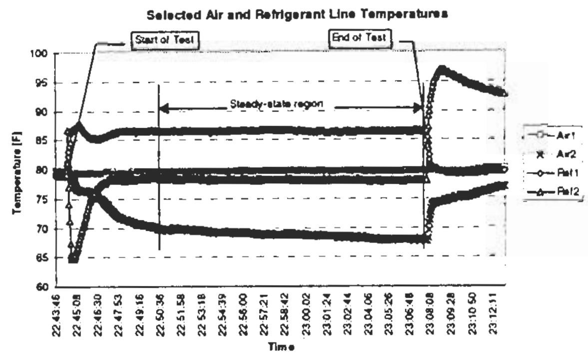

Figure 4. Typical data set from the test-bench

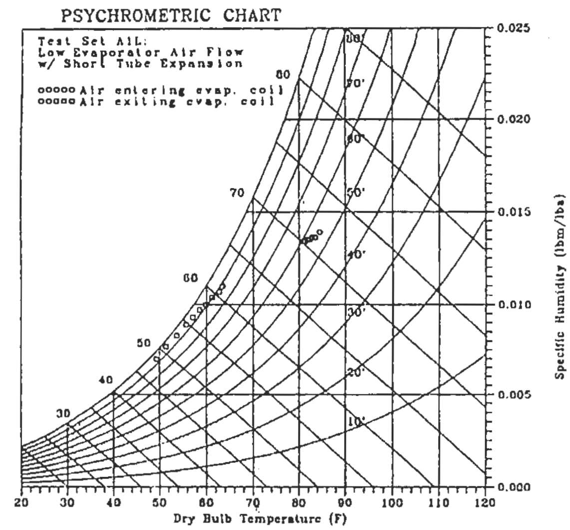

Figure 5. Psychrometric chart with overlaid entering and leaving air properties for low evaporator airflow tests using STO expansion in an uncontrolled environment

15 to 20% when sizing new equipment (Heald, 1988) and to stay outside of the band of uncertainty of the air-side capacity of these tests.

Cooling-equipment efficiency becomes critical when the operating cost of the cooling equipment is increased significantly by inefficient operation. Let "normal efficiency" be defined as, $\eta_{norm}=P_{out}/P_{in}$. Let the "normal cost of operation" be defined as, $Cost_1=P_{in}Rate$. If the efficiency for a given cooling load is reduced by 10% it can be shown that,

$Cost_2=P_{in}Rate/(0.9)$, which means the operating cost will increase by more than 11%. For the purpose of this analysis, a 15% decrease in efficiency from normal is considered the "critical point" relative to operating cost.

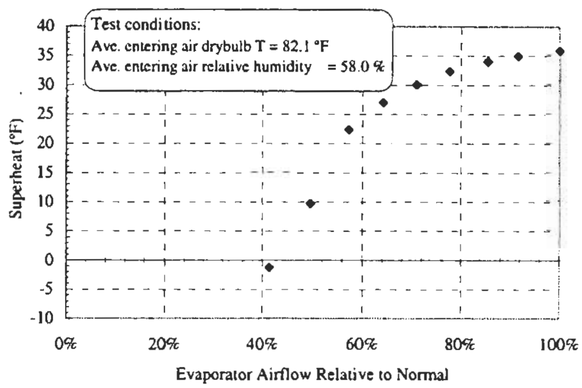

Figure 6. Superheat for low evaporator airflow tests using STO expansion in an uncontrolled environment

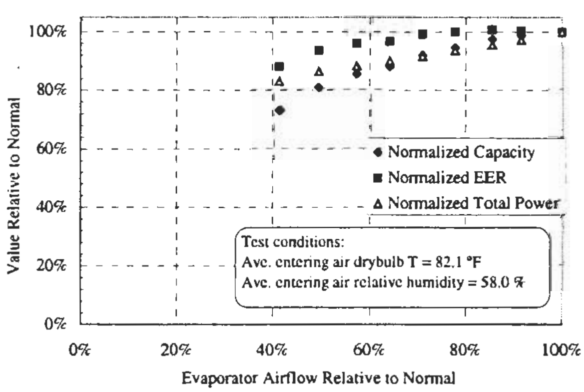

Figure 7. Normalized capacity, total power, and EER for low evaporator airflow tests using STO expansion in an uncontrolled environment

The equipment safety becomes critical when it is compromised by potentially damaging operating conditions such as liquid slugging or overheating. At the heart of any air-conditioning system is the compressor. Many times, replacing the compressor alone will justify replacing the entire condensing unit from a cost standpoint. In addition, when the condensing unit is replaced, care must be taken to be sure that the evaporator coil is properly matched to the new condensing unit. Properly matched components will minimize refrigerant flow, refrigerant charge and discharge pressure while maximizing the capacity and efficiency. Newer evaporator coils are designed with enhancements that are better suited to take advantage of today's high efficiency condensing units. Tests have shown that a 1992, 10 SEER condensing unit installed in a system with a 1970's vintage evaporator coil can result in a significant loss of efficiency, capacity and even shortened compressor life (Duffy 1992). For these reasons, the primary concern related to equipment safety and longevity is that of the compressor.

As seen in Figure 6, low evaporator airflow can result in slugging the compressor with liquid refrigerant if the superheat is allowed to decrease to zero. The best way to avoid slugging is to provide adequately superheated vapor to the suction side of the compressor, however, be careful not to allow the superheat to get too high as this will result in overheating the compressor and eventually insulation breakdown and compressor failure. Small systems are typically designed to provide 12 to 20°F superheated vapor to the compressor. For this analysis, a 40% reduction in superheat was considered as the "critical point" with respect to compressor safety. This is well above the uncertainty for the superheat calculation.

Finally, the "critical point" driving the selection of low evaporator airflow indicators was the smallest airflow reduction that resulted in either the capacity, efficiency, or equipment safety indicator reaching its respective "critical point". From Figure 7, for the STO system, the cooling capacity of the system was reduced by 15% at about 57% of normal airflow (43% reduction). The efficiency was reduced by 12% at about 41% of normal airflow (59% reduction). From Figure 6, the superheat was reduced by 40% at about 57% of normal airflow (43% reduction). Therefore, the low evaporator airflow "critical point" corresponded with that of the capacity and the equipment safety (superheat) and was defined as 57% of normal evaporator airflow.

SUMMARY

This paper summarizes the literature supporting the original work, describes the experimental apparatus and procedure, and presents a small portion of the data obtained from the original work as an example to the method described herein.

The three most common system degradations are identified as improper airflow, improper charge, and electrical problems. A procedure which takes advantage of tests performed in an uncontrolled environment to identify temperature-based indicators is presented. The original work has showed that time and money can be saved by identifying temperature-based indicators using the described test bench in an uncontrolled environment.

Performance data from the low evaporator airflow tests on a short-tube orifice (STO) system in an uncontrolled environment are presented in this paper. A procedure for identifying indicators is presented that uses the performance parameters capacity, efficiency, and superheat which are related to occupant environment, cost of operation, and equipment longevity, respectively. A "critical point" relative to the three performance parameters is defined to help identify indicators of a given degraded condition.

Temperature-based indicators identified in the original work as a result of the procedure herein are not presented. Complete test results including low evaporator airflow for the STO system in a controlled environment and for the TXV system in both the uncontrolled and controlled environment were presented in Watt (1997). Results from other degraded conditions including improper charge and blocked condenser coil for both the STO and TXV systems were also presented by Watt. Temperature-based indicators that were identified for all of the above-mentioned degraded conditions using the procedure presented in this paper were presented in detail by Watt.

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